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NASW-2879

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THE AEROSPACE CORPORATION

Aerospace Report No. ATR-76(7580)-1

FINAL REPORT

Reduction and Analysis of ATS-6 Data

Contract: NASW-2879

Period of Performance:

9 February 1976 to 31 October 1976

G. A. Paulikas and J. B. Blake

Space Sciences Laboratory

NOVEMBER 1976

Ivan A. Getting Laboratories

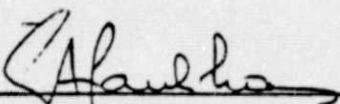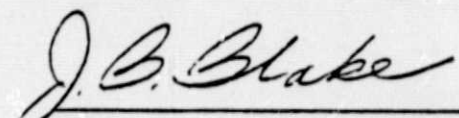THE AEROSPACE CORPORATION

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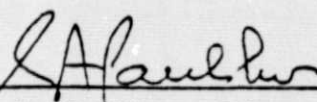
FINAL REPORT

Reduction and Analysis of ATS-6 Data

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Prepared By:

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I.   Introduction

This report summarizes the work performed under NASA Contract
NASW-2879 at The Aerospace Corporation. The tasks performed under this contract
consisted of the reduction of data obtained by The Aerospace Corporation experiment
on ATS-6 and of scientific analysis of the data. During the period covered by this
contract significant progress was made in both reduction and analysis of ATS-6 data.
Virtually all of the data obtained in 1974 have been reduced and more than 230 days of
data obtained in 1975 have also been reduced. At the same time we have also reduced
complementary ATS-1 data obtained during the shift of ATS-6 to the eastern hemi-
sphere in early to mid 1975.

Analysis efforts concentrated on clarifying the relationship we had discovered
between the direction of the interplanetary magnetic field and the fluxes of energetic
electrons at the synchronous altitude. We also developed a simple model of the
energetic electron environment as observed by ATS-6 and extended a simple empirical
relationship which can be used to predict the maximum energetic electron flux to be
expected at the synchronous orbit. These efforts are described below.

II.   Progress in Data Reduction

    A.   ATS-6 Data Reduction

            During FY76 we concentrated our resources on the development of an
efficient data reduction program to handle the ATS-6 data and also developed several
data analysis and data presentation programs. These programs became fully operational
and since early 1976 routine data reduction has proceeded, interrupted only by the
inevitable machine hardware and systems software programs and the move of the
Aerospace Laboratories to new facilities during the summer of 1976.

            The status of ATS-6 data reduction is summarized below:

    1974 data: All data from turn-on (Day 166) through the end of the
                        year have been reduced with the exception of about 17
                        days of data

    1975 data: All data from Day one through Day 230 have been reduced,
                        with the exception of 12 days of data. In addition 12 days
                        of data in the vicinity of Day 280 have been reduced.

    1976 data: Data obtained during the March 30 - April 5 solar proton
                        event have been reduced

            To date, therefore more than 400 days of data have been reduced. This
is about one-half of the total data obtained by the Aerospace experiment since ATS-6
launch. We anticipate no difficulty in continuing the pace of reduction (30-40 day of
data/week of work) under the follow-on contract expected shortly. By early 1977 we
expect to have completed the first pass through all data available to date; at that time
we expect to return and fill the gaps (17 day in 1974, 20-25 in 1975, ...) in the reduced
data.

            All reduced data are stored on tape, in several formats, suitable for
transfer to the National Space Science Data Center.

B. ATS-1 Data Reduction

The ATS-1 spacecraft, launched in late 1966 and stationed at 150°W longitude in the synchronous orbit, contains a particle spectrometer designed and developed by The Aerospace Corporation. The experiment on ATS-1 continues to be operational and data were acquired from it in mid-1974, during the early operation of ATS-6, as well as in early-to-mid 1975, during the move of ATS-6 to the eastern hemisphere. We have requested, and NASA has approved, acquisition of ATS-1 data during the return of ATS-6 from 30°E longitude to a position near 140°W.

All ATS-1 data, acquired in 1974 and 1975 have been processed.

III.   Scientific Analysis

A.   Modulation of Trapped Electrons by Interplanetary Magnetic Field Boundaries

1.   Introduction

We have observed a periodicity in the magnetospheric energetic electron fluxes (E˙ 1 MeV) at 6.6 R_e associated with the passage of sector boundaries of the interplanetary magnetic field. The changes in the electron flux, associated with each boundary passage, are the major intensity excursions of the electron fluxes during conditions of low. solar activity. Furthermore, maximum intensity reached by the energetic electrons in the intervals between sector boundary passage is dependent upon the direction of the interplanetary magnetic field.

Changes in the intensity of trapped energetic electrons which could be associated with changes in the conditions existing in the interplanetary medium, and thus ultimately with the properties of magnetic field and plasma structure of the solar atmosphere, have been reported by Williams (1966) and Rothwell (1968). The observations which led these authors to conclude that the outer zone was markedly responsive to the sector structure of the interplanetary medium were obtained in the time interval near solar minimum in the middle 1960's. In 1968 we used ATS-1 data on energetic electrons which were obtained between late 1966 and early 1968 at the synchronous orbit in an attempt to verify the conclusions of Williams and Rothwell. Although the experimental situation in a synchronous orbit is somewhat "cleaner" than observations made aboard low-altitude spacecraft or high-altitude spacecraft in elliptical orbits, we failed to establish that any close correlation existed between changes in the electron fluxes observed at 6.6 R_e, and changes in the direction of the interplanetary field. To be sure, sector boundary passages did give rise to major excursions in the flux levels of energetic electrons; however equally large excursions also occurred when there were no IMF boundaries in the vicinity of the earth. These conclusions, now more than five years old, were once again checked in the course of the present study using the sector boundary catalog prepared by Svaalgard (1975).

We were thus surprised to find that ominidirectional electron fluxes (hourly averages), as determined from data obtained by The Aerospace Corporation experiment aboard ATS-6 in 1974 and 1975, exhibit a very pronounced periodicity which is very clearly associated with the passage of interplanetary magnetic-field sector boundaries. ATS-6 was stationed at 6.6 R_e and at 94^OW during the time period under consideration; the experiment which yielded the data presented here is fully described in Paulikas et al. (1975). Figure 1 illustrates the observations made at noon local time. Similar plots have been constructed for other local times and these plots exhibit identical periodicities. A limited set of data from the synchronous spacecraft ATS-1, located at 150^OW, and ATS-5, located at 105^OW, also are available to us for portions of the time period under discussion. (ATS-5 data were graciously provided by C. E. McIlwain). Such comparisons as we have made indicate that ATS-1, ATS-5 and ATS-6 all observe the modulation. Clearly the entire outer magnetosphere is involved. Evidently, strong, periodic modulation of the outer-zone trapped-particle intensities by the interaction between the magnetosphere and the interplanetary medium is a function of the general level of solar activity and emerges as the dominant process affecting the outer zone during conditions of solar minimum. During periods of high solar activity, the periodic modulation is masked by the more-or-less irregular occurrence of magnetic storms which destroy the coherence that the energetic electron fluxes would otherwise be expected to develop in response to interplanetary conditions.

2.   Discussion

The outer-zone energetic electrons observed by ATS-6 are one of the end products of the interaction of the solar wind with the earth's magnetosphere. The magnetospheric substorm is the basic process which energizes magnetospheric plasma and transports these energetic particles into the stable-trapping region of the magnetosphere (McPherron et al., 1973). In the absence of magnetic storms, the temporal evolution of the energetic electron population is a measure of the relative strength of the source (i.e., substorms) as compared to particle sinks. Our observations can be considered as representing an averaged, smoothed output of the solar wind-magnetosphere engine, with the equilibrium level of energetic electron fluxes indicative of the rate of occurrence of substorms, and hence the rate of "quiescent" energy transfer into the magnetosphere (Russell, 1974). In contrast, the changes in the electron fluxes at the time of boundary passage are associated with major disruption of the energetic electron population by magnetic storms.

We interpret our results using the phenomenological studies of Arnoldy (1974), Burton et al., (1975), Burch (1973), and Russell and McPherron (1973). The thrust of the findings of these authors, as summarized in the review of Russell (1974), is that the energy flow from the solar wind into magnetosphere mimics in some ways the behavior of a half-wave rectifier familiar in electronic applications. The input of energy into the magnetosphere proceeds only if the magnetosphere sees a southward component of the interplanetary magnetic field; a northward IMF component apparently inhibits the transfer of energy into the magnetosphere. Thus, to first approximation, the dynamics of the magnetosphere are a function of the orientation the magnetosphere in solar-equatorial coordinates (the natural coordinates of the flow of the solar wind plasma). The geometrical arguments and coordinate transformations required to determine whether the magnetosphere sees a net northward or a net southward component of the interplanetary magnetic field are somewhat complex and the reader should refer to the paper of Russell and McPherron (1973) for a complete and critical discussion of the problem. For our present purposes, we can summarize briefly: the interaction between solar wind and magnetosphere is expected to be strongest because the magnetosphere is immersed in a southward pointing interplanetary field in the spring, when the earth is in a (−) sector of the interplanetary field, and strongest in the fall, when the earth is in a (+) sector of the interplanetary field.

The data obtained during the fall of 1974 and presented in Figure 1 are consistent with this picture. The energetic electron fluxes appear to build up to higher levels during (+) sectors (i.e., generally southward IMF) than during (−) sectors. Note also that (−) to (+) sector transitions cause much deeper depressions in the electron flux than (+) to (−) transitions. Examination of the behavior of D_{st} for this period shows that a magnetic storm is associated with each (−) to (+) transition.

A limited set of data obtained in early 1975 (Fig. 2) verifies the expectation that in spring (−) sectors are more effective generators of energetic electron fluxes. The IMF sector structure during the time period covered by Fig. 2 is broken by days of mixed polarity; nevertheless, the data of Fig. 2 are, if anything, an even more striking demonstration that the level of energetic electron flux at 6.6 R_e is a strong function of the direction of the interplanetary field.

At this stage of the data analysis we cannot unequivocally separate temporal changes in the electron flux from changes in the geometry of the trapping region. The work of Owens and Frank (1968) very clearly shows that the region around the earth containing energetic particles expands and contracts. ATS-6 observations, by themselves, cannot provide information regarding the extent of the trapping region. If we focus our attention on the properties of the region near ATS-6 we find, using data from the UCLA magnetometer on ATS-6 (graciously made available by R.L. McPherron), that during the time periods of Figs. 1 and 2 there do not appear to be any significant changes in the local field geometry at ATS-6 which is a function of the gross direction of the interplanetary field as inferred by Svalgaard (1975).

It must be recalled that, because of drift shells splitting, a measurement of the omnidirectional flux by our experiment at one local time at the synchronous orbit represents the sum of the flux which exists over a range of L values at other local times. Our data have global rather than local properties. In addition, it is well known that large drift loss cones can develop in the angular distribution at synchronous altitude because of the proximity of the synchronous orbit to the trapping boundary. Such changes in the angular distribution would be interpreted by our experiment as flux changes. There are suggestions in the data, for example, in comparisons of relative flux changes at ATS-1, ATS-5 and ATS-6 as a function of IMF direction, that there may indeed be changes in the average pitch-angle distribution of energetic electrons (and therefore changes in the geometry of the trapping region) which are a function of the interplanetary field direction.

Correlations between the state of the magnetosphere and interplanetary conditions appear to be most successful when the magnetospheric parameters used in such studies represent some global characteristic of the magnetosphere. The auroral electrojet index A_e (Arnoldy, 1971), properties of polar magnetic fields (Burch, 1973), the size of the polar cap (Akasofu, 1975) and the D_{st} index (Burton, et al., 1975) are examples of such global quantities. We can now add the energetic electron fluxes at the synchronous orbit to the list of indicators of the coupling strength between the interplanetary medium and the magnetosphere.

B.   Preliminary ATS-6 Electron Environment Model

1.   Introduction

    This portion of our report describes a very preliminary model of the energetic electron environment at the synchronous altitude as derived from ATS-6 data. Virtually all of the data obtained by ATS-6 during 1974 have now been reduced and analyzed for this purpose. The data base covers the period from Day 165 (1974) through Day 365 (1974). The model derived here should thus be reasonably representative of the conditions to be expected during the years near the minimum of solar activity for geographic longitudes (at the synchronous orbit) in the vicinity of 94°W.

2.   Results

    The usual $P(F > F_x)$ plot is presented in Fig. 3 and compared against the predictions of the AE 4 model (Singley and Vette, 1972). Note that AE-4 does not predict any variation of the electron radiation at $L = 6.6$ R_e with solar cycle; in addition the predicted dependence of the flux with B/B_0 (i.e., magnetic latitude or, in the case of the synchronous orbit, longitude) for AE-4 is very slow. Thus the comparison is not entirely fair, but since AE-4 is the accepted standard model, such a comparison is the best that can be done. The ATS-6 results indicate a slightly lower flux than AE-4 for E_e 700 keV; there is agreement between AE-4 and ATS-6 for $E_e > 1.55$ MeV and ATS-6 data indicate considerably higher fluxes for $E_e > 3.9$ MeV.

    Figure 4, taken from Singley and Vette which describes the AE-4 model, shows that ATS-6 time averaged electron spectrum (including a 140-600 keV channel not shown in Figure 3) superimposed on the data base used to construct the AE-4 model and the AE-4 spectrum. The ATS-6 spectrum appears to be somewhat harder than the AE-4 spectrum for energies above 700 keV.

C.   Upper Limit on Trapped Electron Flux.

    We have discovered an empirical relationship which predicts the maximum equilibirum flux of energetic electrons that can exist at the synchronous orbit. Although we have no theoretical justification for this relationship, data spanning

more than one 11-year solar cycle, two orders of magnitude in electron energy and several locations in space (i.e., on and off the magnetic equator) can be systematically ordered so that the maximum integral omnidirectional electron flux above any energy can be approximately predicted. This information should be of value for the prediction of the maximum radiation dosages which spacecraft at the synchronous altitude will ever encounter.

The analysis proceeds as illustrated in Figure 5. Using $P(F > F_x)$ plots which predict the probability of observing an integral flux greater than F_x for a given energy threshold, an extrapolation is made using the straight portion of the $P(F > F_x)$ curves to obtain I^*. The $\log_{10}$ of this quantity is then plotted as a function of the square root of the energy threshold. Figure 6 summarizes the data obtained from ATS-1 (1966-1968) and ATS-6 (1974-1975). Also included, at 40 keV, are data obtained in 1962. A simple, straight line described by the equation

$$\log_{10} I^* \ (cm^{-2} sec^{-1}) = 2.53 \ \sqrt{E(MeV)} + 8.5$$

describes the experimental data to the accuracy warranted.

Elements of this procedure have already been described by Schulz and Lanzerotti (1974). The ATS-6 data confirms and extends these results to the relativistic region at 4 MeV and beyond, of interest when considering the effects of fission-debris electrons. Note that our empirical formula addressed equilibrium conditions; it is reasonable to expect that transient excursions past the flux limits given in Figure 6 are possible.

IV.   Acknowledgements

V.   References

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Figure 1.   Hourly averages of energetic electron countrates observed in the late summer and fall of 1975 by ATS-6 and ATS-1 are plotted as a function of Day Number, 1974. Also plotted (at the top of the figure) is the polarity of the interplanetary magnetic field as inferred by Svalgaard (1975). Local time for all particle data is local noon; the sector boundary transitions are assumed to occur at 0000 UT for the days indicated. Circles and triangles are ATS-6 observations of >3.9 and >1.6 MeV electrons respectively, squares are ATS-1 observations of >1.9 MeV electrons. For emphasis we have shaded those portions of the curves where the $E_e > 1.6$ MeV countrates exceed 10^3/sec and the $E_e > 3.9$ MeV countrates exceed 10/sec.

Figure 2.   Hourly averages of energetic electron countrates observed in the spring of 1975 by ATS-6 and ATS-1. All other comments from the caption of Figure 1 apply. The IMF sector structure during this period exhibited some days of mixed polarity, these days are indicated by cross-hatching.

Figure 3.   Plots of the probability $P(F > F_x)$ of observing a flux of electrons greater than F_x above thre integral thresholds. ATS-6 data (solid curves) and AE-4 predictions (dashed curves) are shown. The ATS-6 curves were constructed using 181 days of data obtained between Day 165 (1974) and Day 365 (1974) while ATS-6 was located near 94°W.

Figure 4.   This figure, taken from Singley and Vette shows the AE-4 data base for $L = 6.6$ R_e, the AE-4 model and the ATS-6 time averaged electron spectrum. An additional channel of ATS-6 data, covering 140-600 keV, is shown here in addition to the three channels of ATS-6 data used in Figure 3.

Figure 5. $P(F > F_x)$ plot taken from Schulz and Lanzerotti, illustrating the definition of I^*.
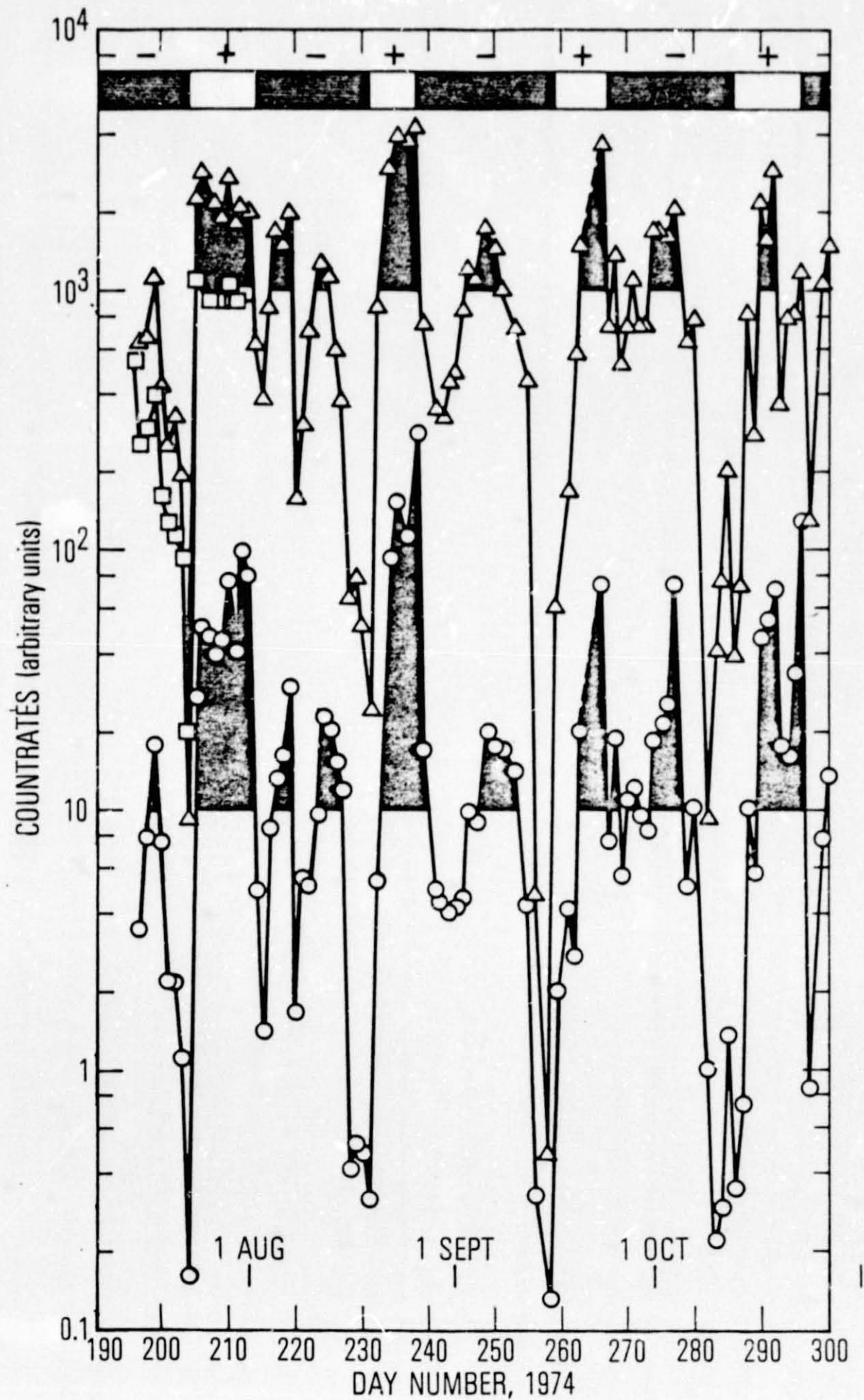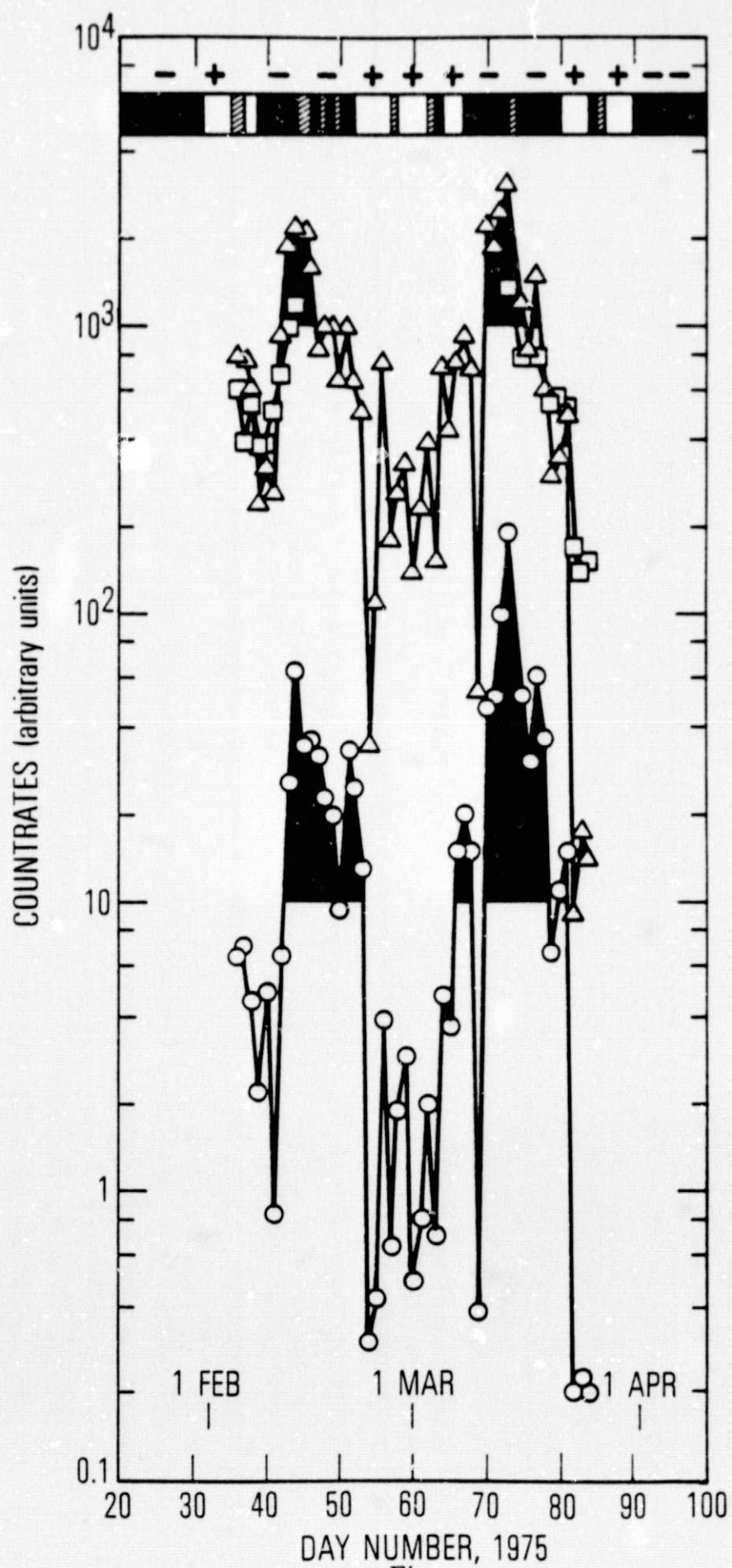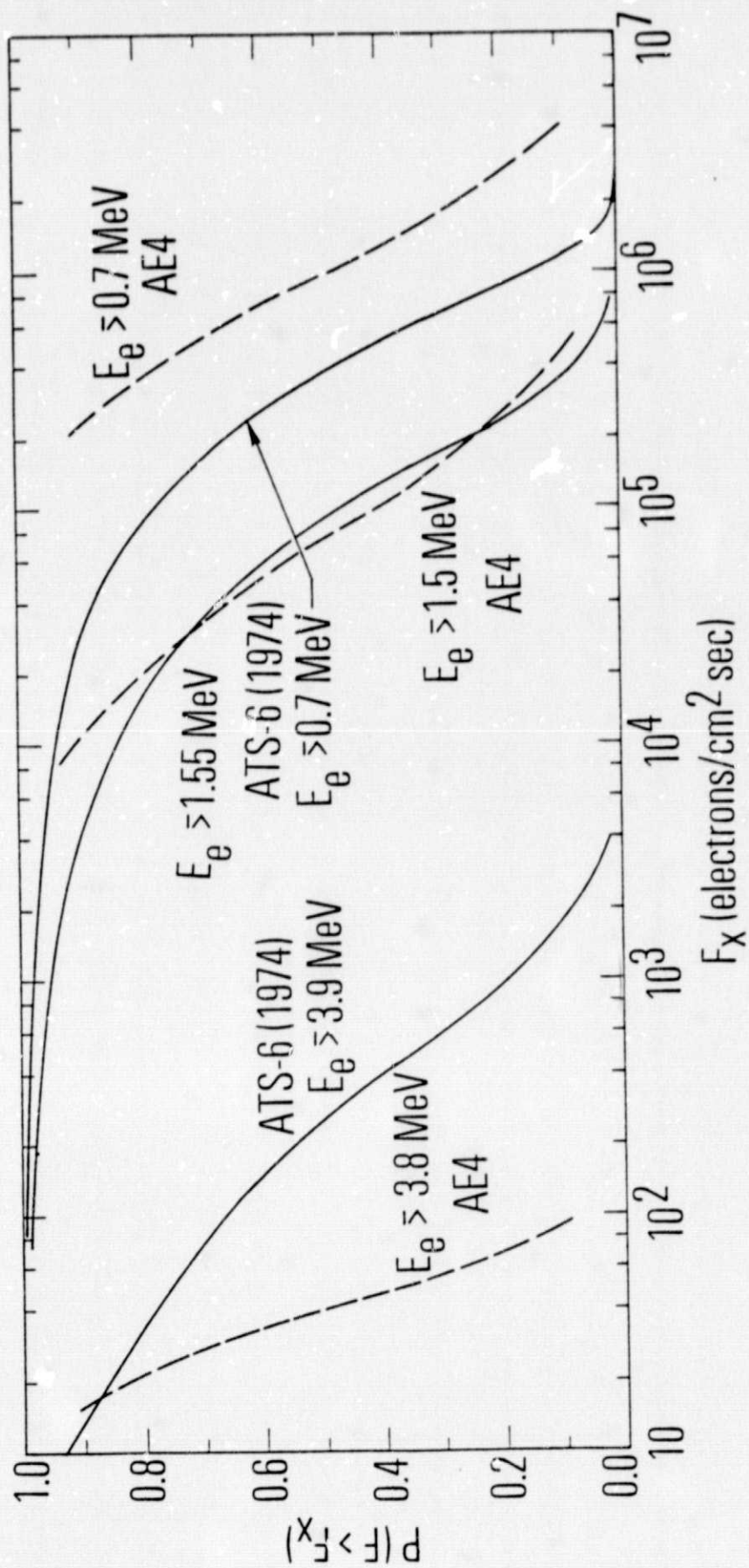
Figure 6.   Plot of $\log_{10} I^*$ as a function of $E\frac{1}{2}$.
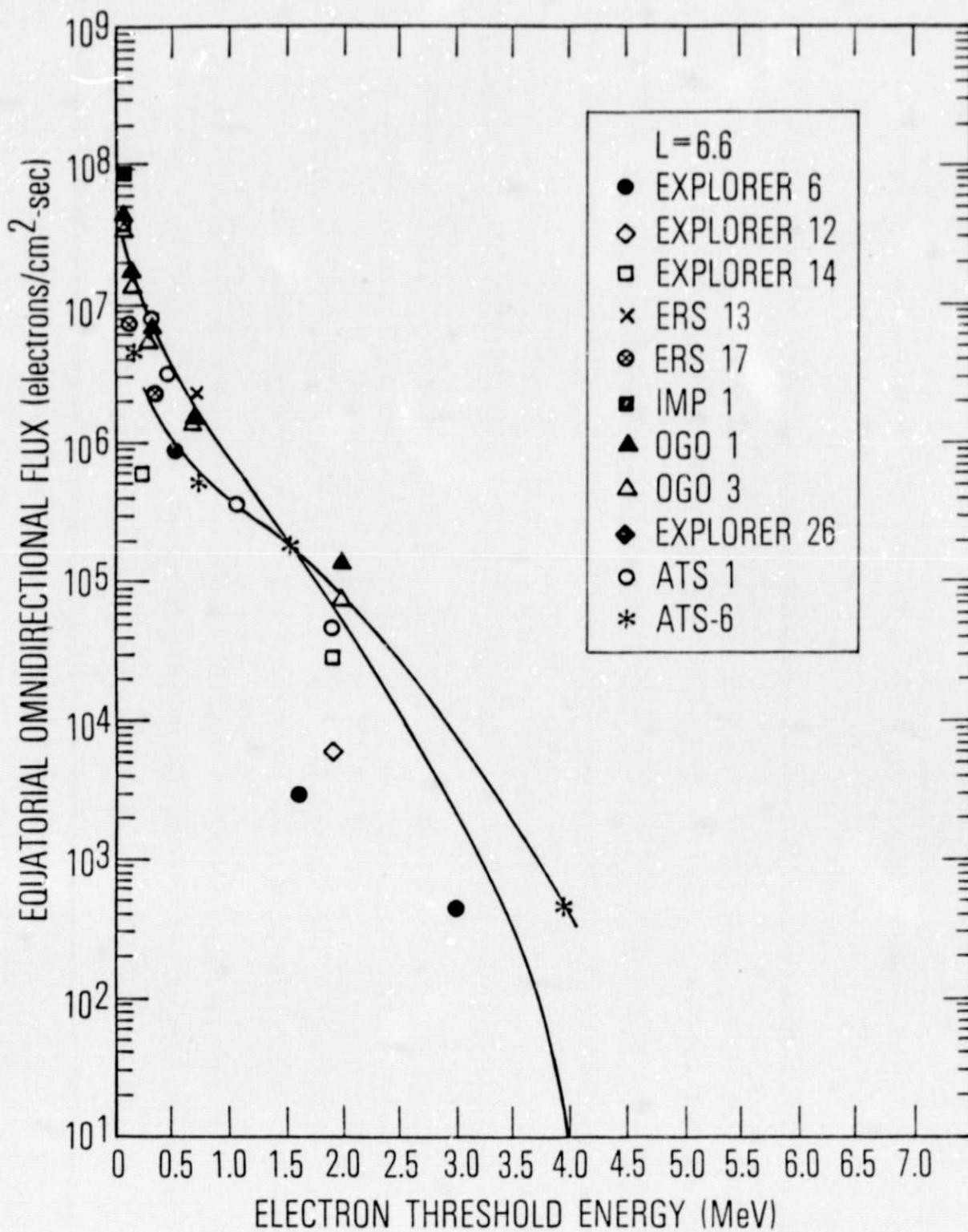
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